

Modeling of lead acid batteries in PV systems

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Abstract

The study of a photovoltaic system necessitates in a first time equivalent models of the main components such as PV generator model, storage element (batteries). The knowledge of their electrical characteristics remains a key factor in the simulation analysis. The battery behavior has been largely described in the literature by many authors such as Shepherd, Monegon, Mayer, Facinelli, Hyman, and CIEMAT. Most of the models require the knowledge of appropriate parameters. Batteries remain a complicated element, since they are the only dynamic element in a PV system. In fact many phenomenons can occur such as charge and discharge. Many parameters vary during these processes: voltage, current, density, temperature, resistivity...etc. The selected model is that elaborated by CIEMAT. This model is general and normalized with battery capacity, it necessitate few input parameters, it takes into account the discharge, the charge and the overcharge processes, and can be applied for wide range of lead acid batteries used in PV systems. The CIEMAT (Copetti) model presents a good performance to represent dynamic and complex battery operation. This paper reviews this general lead acid batteries model and it agreement with experimental data obtained from tests with in photovoltaic systems. In order to validate these models, the behavior of different battery cycling currents has been simulated. Results obtained have been compared to real data in two PV systems, the first one with Varta Solar 100Ah-12V and the second one with Tudor 800 Ah-2V. For checking the validity of the mathematical model, the results of numerical simulation are compared with experimental data.

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battery storage; battery modeling; lead acid battery; Storage system; PV

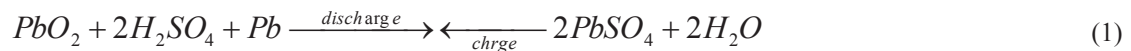
I INTRODUCTION

Battery is a crucial component in a stand-alone photovoltaic system. It acts as a dumper by allowing the storage of excess energy from the PV array and, provides energy for the loads during night or non-sunny

days. It can be considered as a stabilizer since it feeds the loads with constant voltage. Most of the batteries used in PV systems nowadays are lead acid batteries. Batteries remain a complicated element, since they are the only dynamic element in a PV system. In fact many phenomena can occur such as charge and discharge. Many parameters vary during these processes: voltage, current, density, temperature, resistivity...etc. This leads to a complicated behavior of this element and thus makes predictions of the state of charge much more complicated. The battery behavior has been largely described in the literature by many authors such as Shepherd, Monegon, Mayer, Facinelli, Hyman, and CIEMAT [1]. Most of the models require the knowledge of appropriate parameters. This paper reviews this general lead acid batteries model and its agreement with experimental data obtained from tests with in photovoltaic systems. For checking the validity of the mathematical model, the results of numerical simulation are compared with experimental data. The experimental data are available for three days of Varta solar 100 Ah battery operations. To complement this assessment, the Copetti model was applied to a storage system through Tudor 800 Ah battery for a period of ten days of operation. This battery is then integrated into a photovoltaic system. Note that this storage system has more capacity than the previous ($C_{10} = 800$ Ah).

II BATTERY MODELING

Lead acid battery is the most used storage element in PV system. The main function of lead acid batteries is the storage and the supply of energy in a PV system. The stored energy is chemical can be converted into electrical and vice versa. The electrochemical reactions are described by the following reactions.



In general, the battery behavior is described by its voltages.

$$V = V_{oc} \pm I R \quad (2)$$

Where V_{oc} is the open circuit voltage and R is the internal resistance. The current I is positive during charge and negative during the discharge. The internal resistance is variable, and depends on other parameters such as capacity, charge/discharge current, temperature ...etc.

Many models have been developed to describe the voltage evolution taking into account the variation of the internal resistance. Most of the proposed models based on the experimental identification of the intrinsic parameters for each type of battery.

The advantage of the battery model developed by CIEMAT is its ability to cope with a wider range of lead acid batteries and requires few manufacturers' data technological parameters [1][2].

In this model, three processes are considered: discharge, charge and overcharge, and their mathematical formulations are given by the following equations.

A. Discharge voltage equation

The discharging is given by the following equation:

$$V = [2.085 - 0.12 (1 - SOC)] - \frac{I}{C_{10}} \left(\frac{4}{1 + I^{1.3}} + \frac{0.27}{SOC^{1.5}} + 0.02 \right) (1 - 0.007 \Delta T) \quad (3)$$

The first term represents the open circuit voltage variation with the state of charge (electrolyte concentration) and the second is due to the internal resistance variation which is represented by the sum of series resistances of the other different phenomenons.

The temperature variation ΔT is given by Equation 3 with $T_{ref}=25^{\circ}\text{C}$.

$$\Delta T = T - 25 \quad (4)$$

The state of charge (SOC) is defined as:

$$SOC = 1 - \frac{Q}{C} \quad (5)$$

where the ratio between the charge delivered at the time of interest ($Q=I.t$) and the battery capacity (C) represents the depth of discharge.

The efficiency during discharge is assumed to be 100%; however, the total amount of useful charge available during discharge is limited by the current rate and temperature given by the capacity. This last is normalized with respect to discharge current corresponding to C_{10} rated capacity (I_{10}) is:

$$\frac{C}{C_{10}} = \frac{1.67}{1 + 0.67 \left(\frac{I}{I_{10}} \right)^{0.9}} (1 + 0.005 \Delta T) \quad (6)$$

When the discharge current tends to zero, the maximum capacity that can be removed is about 67% over C_{10} capacity at 25°C .

B. Charge voltage equation

The charging equation is given by the following equation:

$$V = [2 - 0.16 \text{ SOC}] + \frac{I}{C_{10}} \left(\frac{6}{1 + I^{0.86}} + \frac{0.48}{(1 - \text{SOC})^{1.2}} + 0.036 \right) (1 - 0.025 \Delta T) \quad (7)$$

In this case, the state of charge (SOC) is function of the efficiency conversion η_c and SOC_0 . The SOC equation is given as:

$$SOC = \text{SOC}_0 + \frac{\eta_c Q}{C} \quad (8)$$

and the efficiency equation is :

$$\eta_c = 1 - \exp \left[\frac{20.73}{\frac{I}{I_{10}} + 0.55} (SOC - 1) \right] \quad (9)$$

C. Overcharge voltage equation

The overcharge phenomenon (gassing) can be represented by the following exponential function:

$$V = V_g + (V_{ec} - V_g) \left[1 - \exp \left(\frac{0.95 C - Ah_{restored}}{I \tau} \right) \right] \quad (10)$$

V_g : gassing voltage

V_{ec} : final charge voltages

$$V_g = \left[2.24 + 1.97 \ln \left(1 + \frac{I}{C_{10}} \right) \right] (1 - 0.002 \Delta T) \quad (11)$$

$$V_{ec} = \left[2.45 + 2.01 \ln \left(1 + \frac{I}{C_{10}} \right) \right] (1 - 0.002 \Delta T) \quad (12)$$

$Ah_{restored}$ represents the ampere-hours stored in the battery with regard to the battery capacity C for the charge current I during this hour. We assumed that 95% of capacity already was restored in the starting of the overcharge.

The time constant τ is inversely proportional to charge current intensity and, as an approximation, can be written:

$$\tau = \frac{17.3}{1 + 852 \left(\frac{I}{C_{10}} \right)^{1.67}} \quad (13)$$

Therefore, the voltage evolution during the charge process is represented by Equation (7), up to the voltage of gassing ($V_c \leq V_g$) and by Equation (10) for overcharging ($V_c > V_g$) until a constant final voltage (V_{ec}) is reached.

III PV SYSTEMS WITH BATTERY

The simplest solutions have certain drawbacks - the most obvious one being that incase of PV powered pump or fan could only be used during the daytime, when the sun is shining. To compensate for these limitations, a battery is added to the system. The battery is charged by the solar generator, stores the energy and makes it available at the times and in the amounts needed. In the most remote and hostile environments, PV-generated electrical energy stored in batteries can power a wide variety of equipment. Storing electrical energy makes PV systems a reliable source of electric power day and night, rain or shine. PV systems with battery storage are being used all over the world to power lights, sensors, recording equipment, switches, appliances, telephones, televisions, and even power tools

PV systems with batteries operate by connecting the PV modules to a battery, and the battery, in turn, to the load. During daylight hours, the PV modules charge the battery. The battery supplies power to the load whenever needed. The batteries used in PV systems are often similar to car batteries, but are built somewhat differently to allow more of their stored energy to be used each day. They are said to be deep cycling. Batteries designed for PV projects pose the same risks and demand the same caution in handling and storage as automotive batteries. The fluid in unsealed batteries should be checked periodically, and batteries should be protected from extremely cold weather.

A solar generating system with batteries supplies electricity when it is needed.

How much electricity can be used after sunset or on cloudy days is determined by the output of the PV modules and the nature of the battery bank. Including more modules and batteries increases system cost, so energy usage must be carefully studied to determine optimum system size. A well-designed system balances cost and convenience to meet the user's needs, and can be expanded if those needs change.

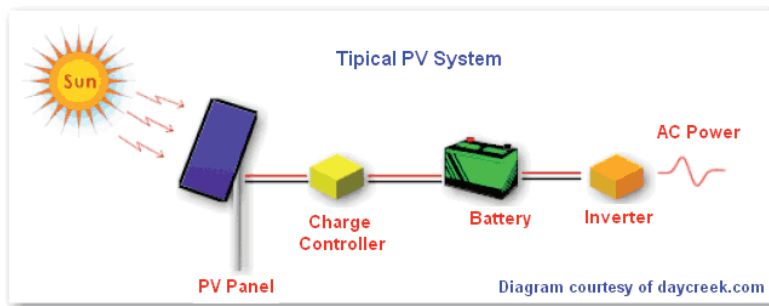


Figure 1: Typical PV System

IV SIMULATION OF LEAD ACID BATTERY IN PV SYSTEM

The CIEMAT model presents a good performance to represent dynamic and complex battery operation as mentioned in references [3][4]. Furthermore, we explore the usefulness of this model for PV design purposes. For this, we developed a PV system simulation program, working on an hourly basis. The values of root mean square error (RMSE) [5] that indicate of the models performance to represent the battery behavior during the processes are for Varta solar battery 0.052 for charge and 0.061 for discharge.

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N \left[\frac{C_i - M_i}{M_i} \right]^2 \right]^{1/2} \times 100 \quad (14)$$

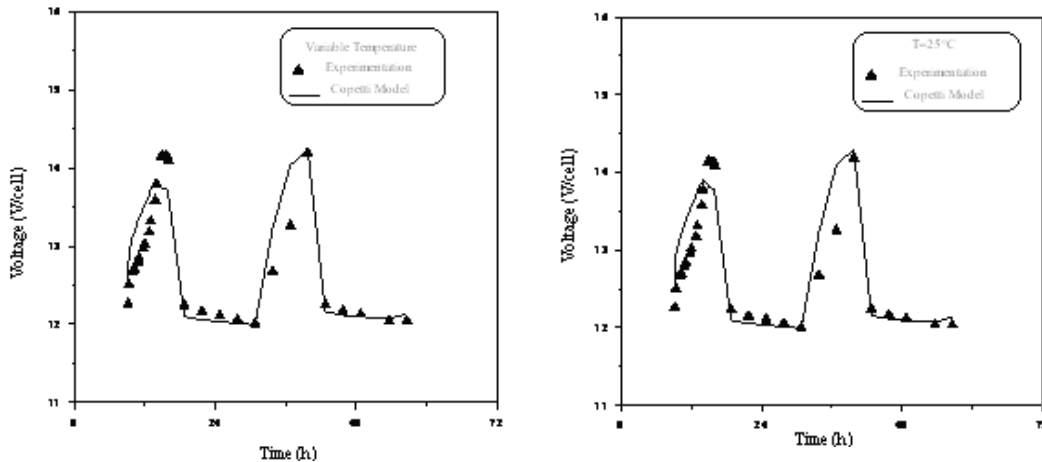


Figure 2: Simulation of VARTA Solar 100Ah battery in PV system

A simulation study was done with CIEMAT model of a battery, in two different PV systems. The first system is the central Matriouane with battery type TUDOR 800Ah -2V, the second is a small PV system with Solar Battery, the type of this battery is VARTA solar 100Ah-12V.

Figures 1 and 2 illustrate the modeling results for different regimes (current charge and discharge variables following the sun for the charge process and according to consumption for the discharge process). We note that the quantity of electricity supplied by PV systems varies periodically. It is highest during times of high radiation (load) and minimum during hours of low radiation (discharge).

The voltage of both batteries while charging back up to the maximum represented by the peaks, the values of these peaks vary with the sunshine. During discharge, the curves have the same gait, the voltage decreases with time.

If we compare Figures 2 and 3 of the simulation of both photovoltaic systems, we note that although the model simulates the discharge for both types of batteries, but differences between the actual and calculated values are observed for the charge of TUDOR battery, it comes to determining the state of charge (SOC) which is easily calculated during the discharge and it is not the case during charging.

To calculate the state of charge for the battery during charging, it must consider the performance of the battery which is itself based on the state of charge, charging current and time of storage (self-discharge).

Determining the state of charge for the battery VARTA Solar was made by measuring the density of the electrolyte and the open circuit voltage, for the battery TUDOR the value of the initial state of charge for the battery was determined from the linear curve of the open circuit voltage according to the state of charge. From the initial conditions of the two types of batteries we have calculate state of charge (SOC) at any time.

V CONCLUSIONS

This work presents an experimental study for two types of batteries in two different PV systems. The model utilized for the simulation of the storage system is the general model CIEMAT (copetti), this model presents a good performance to represent dynamic and complex battery operation, it may serve further as a tool for the electronic design applied to Photovoltaic.

In this way, other results could be evaluated considering parameter variations effects in the life of battery. The aging model describing life time of a battery is useful for an economic analysis.

Accuracy of generalized Copetti model is more than satisfactory approaching most of the problems encountered today in the photovoltaic sector. The results are encouraging, the calculated errors (RECM) are less than 3% for the charging and discharging of the two types of batteries. Copetti model can be considered suitable to be used to simulate a large number of lead acid batteries, particularly those used in the storage of solar energy. The effectiveness of this model was demonstrated during the discharge for both types of batteries, but the results are therefore slightly overestimated during charging which takes into account the overload. These differences arise from the calculation of the state of charge. The operation of the battery depends mainly on its state of charge, temperature, concentration of electrolyte and internal resistivity. It is therefore essential to study the behavior of a battery in a PV system, determine its state of charge at all times. The concentration of the electrolyte is the best indicator of the state of charge, but it is still difficult to measure it on-site PV, however, there is the voltage of battery that is a good indicator.

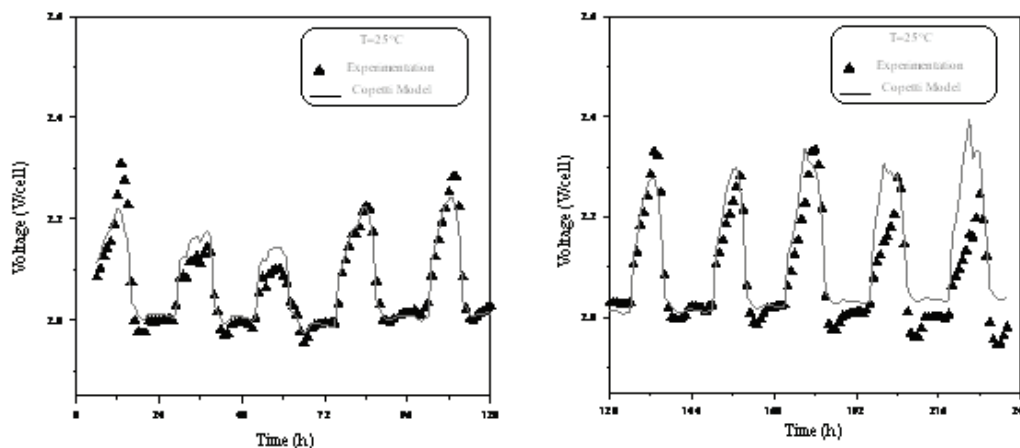


Figure 3: Simulation of TUDOR 800Ah battery in PV system

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